DESCRIPTION

SEMICONDUCTOR DEVICE AND METHOD FOR MANUFACTURING SEMICONDUCTOR DEVICE

Technical Field

The present invention relates to a semiconductor device and a method for manufacturing the semiconductor device. In particular, the present invention relates to a semiconductor device in which zinc oxide is used as a semiconductor material and to a method for manufacturing the semiconductor device.

Background Art

Zinc oxide (ZnO) is one type of II-VI compound semiconductors. The band gap energy of ZnO can be changed by making ZnO into a mixed crystal with MgO, CdO, or the like, and ZnO can have a multilayer structure of quantum well and the like. Furthermore, since the bond energy of an exciton is very large, an application to light-emitting devices is expected. Since ZnO is transparent in the visible range, an application to transparent thin film transistors for driving liquid crystal displays is expected.

Meanwhile, ZnO has a wurtzite structure (hexagonal system). As shown in Fig. 9, ZnO has no center of symmetry

in the c axis direction (vertical direction) and has polarity based on a molecular structure.

That is, ZnO has zinc-polarity (+c polarity) in which three bonds bonding to a Zn atom 51 point downward and three bonds bonding to an oxygen atom 52 point upward, as shown in Fig. 9(a), and oxygen-polarity (-c polarity) in which three bonds bonding to a Zn atom 51 point upward and three bonds bonding to an oxygen atom 52 point downward, as shown in Fig. 9(b).

Here, the above-described polarity refers to an orientation of the above-described bond and does not refer to an element terminating the surface.

It has been already reported that a ZnO thin film having the oxygen-polarity was previously able to be formed by a PMBE (plasma-assisted molecular-beam epitaxy) method on a sapphire substrate (APPLIED PHYSICS LETTERS Vol. 80 No. 8 pp. 1358-1360 (2002); hereafter referred to as "first known technology").

It has been reported that a film of GaN having Ga-polarity was formed on a sapphire substrate and, by controlling the film formation conditions, a ZnO thin film having the zinc-polarity or the oxygen-polarity was able to be formed on the above-described GaN (APPLIED PHYSICS LETTERS Vol. 77 No. 22 pp. 3571-3573 (2000); hereafter referred to as "second known technology").

In addition, a technology has been already reported, in which the polarity of a piezoelectric film of ZnO or the like formed on a substrate was able to be specified (Japanese Unexamined Patent Application Publication No. 2001-144328; hereafter referred to as "third known technology"), as another known technology.

In the above-described third known technology, a piezoelectric film (ZnO film) having a + surface (zinc-polarity) or a - surface (oxygen-polarity) can be formed in accordance with the type of substrate, and the polarity of the piezoelectric film of ZnO or the like formed on a substrate is controlled by changing the film formation conditions, e.g., a heating temperature of the substrate.

With respect to the above-described first known technology, although it has been ascertained by Coaxial Impact Collision Ion Scattering Spectroscopy (CAICISS) that the ZnO thin film formed on the sapphire substrate has the oxygen-polarity. However, substantially hexagonal crystal grains remain in such a ZnO film, the surface shape becomes uneven and, thereby, no ZnO thin film having desired surface smoothness can be attained.

That is, since the surface shape of the ZnO thin film formed by the first known technology has poor smoothness, in the case where a semiconductor device is formed by the use of the ZnO thin film, a current passes through grain

boundaries, and the concentration of electric field occurs on convex portions of crystal grains. Consequently, the operation of the device may become unstable, or the device may be destructed.

According to the second known technology, the polarity of the ZnO thin film can be controlled by changing the film formation conditions. In this manner, the ZnO thin film having the zinc-polarity or the oxygen-polarity can be formed on GaN. However, the substrate temperature rises during the film formation of ZnO on GaN and, thereby, Ga, which is an element constituting GaN, may diffuse into the ZnO thin film.

Since Ga performs a function as a donor to ZnO, if Ga diffuses into the ZnO thin film, the resistance of ZnO is reduced.

Furthermore, it is difficult to control the above-described diffusion and, therefore, variations may result in the device characteristics of the semiconductor device.

In the above-described second known technology, since there is lattice mismatch between GaN and ZnO, lattice defects are introduced to mitigate the lattice mismatch. As a result, the crystallinity of the ZnO thin film is deteriorated and, thereby, deterioration of the electric characteristics results in.

The above-described third known technology discloses

the formation of the piezoelectric thin film having the zinc-polarity or the oxygen-polarity. However, there is no disclosure with respect to the influence exerted by the polarity on the surface shape and the electric characteristics of the thin film. Furthermore, since the material for the substrate is different from the material for the piezoelectric film, deterioration of the crystallinity may result from the lattice mismatch as in the second known technology, and there is a problem in that highly reliable, desired, and excellent electric characteristics cannot be attained.

The present invention has been made in consideration of the above-described circumstances. Accordingly, it is an object of the present invention to provide a semiconductor device, which is provided with a ZnO thin film having excellent surface smoothness and which has excellent crystallinity and excellent electric characteristics, and a method for manufacturing the semiconductor device.

Disclosure of Invention

The inventors of the present invention conducted intensive research in order to attain a ZnO thin film having excellent surface smoothness. As a result, it was found out that a semiconductor device having excellent surface smoothness and crystallinity and excellent electric

characteristics was able to be attained by forming a ZnO thin film on a zinc-polar surface of a single crystal substrate primarily containing zinc oxide.

The present invention was made based on the above-described founding. A semiconductor device according to the present invention is characterized in that a single crystal substrate primarily containing zinc oxide has a zinc-polar surface and an oxygen-polar surface and at least one layer of thin film primarily containing zinc oxide is disposed on the above-described zinc polar surface. In this manner, the thin film having excellent surface smoothness and crystallinity can be formed.

The inventors of the present invention examined the polarity of the above-described thin film, and it was made clear that the thin film had zinc-polarity.

Therefore, the semiconductor device of the present invention is characterized in that the above-described thin film has the zinc-polarity. That is, it is clear that a ZnO-based thin film formed on a zinc-polar surface of a ZnO substrate has the zinc-polarity.

The semiconductor device of the present invention is characterized in that the above-described thin film is composed of a multilayer film and the multilayer film constitute a light-emitting layer or a switching portion.

Specifically, the above-described thin film is composed

of the multilayer film, the multilayer film constitutes the light-emitting layer and, therefore, the light-emitting layer has excellent surface smoothness and crystallinity. Consequently, a light-emitting device, e.g., LED and LD, having excellent electric characteristics can be attained.

Alternatively, the above-described thin film is composed of the multilayer film, the multilayer film constitutes the switching portion and, therefore, even when light is applied to an active layer, change in the electrical conductivity can be suppressed. Consequently, semiconductor devices, e.g., TFT, capable of preventing deterioration of the characteristics of the switching element can be readily attained.

Since the above-described semiconductor device is provided with a ZnO-based multilayer film having excellent surface smoothness and crystallinity, semiconductor devices, e.g., light-emitting elements and thin film transistors, having excellent electric characteristics can be readily attained.

A method for manufacturing a semiconductor device according to the present invention is characterized by including the steps of determining whether a surface of a single crystal substrate primarily containing zinc oxide is a zinc-polar surface or a oxygen-polar surface, and forming at least one layer of thin film primarily containing zinc

oxide on the above-described zinc-polar surface. Furthermore, the method is characterized in that the above-described thin film has the zinc-polarity.

According to the above-described manufacturing method, a desired ZnO-based thin film can be readily and reliably formed on the zinc-polar surface of the zinc oxide substrate.

That is, after determining whether the surface of the ZnO substrate is a zinc-polar surface or a oxygen-polar surface, at least one layer of thin film primarily containing ZnO is formed on the above-described zinc-polar surface. Since the above-described ZnO thin film has the zinc-polarity, the ZnO-based thin film can be readily formed on the zinc-polar surface.

The semiconductor device of the present invention is characterized in that a sputtering apparatus provided with a plasma generation chamber and a film formation chamber is disposed and a sputtering treatment is performed by the use of the sputtering apparatus so as to form the above-described thin film.

According to the above-described manufacturing method, since the film is formed by the sputtering treatment, a semiconductor device having desired electric characteristics can be attained inexpensively. Furthermore, since the plasma generation chamber and the film formation chamber are separated, plasma damage to the semiconductor device can be

minimized.

Preferably, the above-described sputtering treatment is performed by any method selected from among an electron cyclotron resonance plasma sputtering method, an inductively coupled plasma sputtering method, a helicon wave excited plasma sputtering method, an ion beam sputtering method, and a cluster beam sputtering method. Alternatively, the above-described thin film is performed preferably by any method selected from among a molecular-beam epitaxy method, a metal organic chemical vapor deposition method, a laser molecular-beam epitaxy method, and a laser abrasion method.

Brief Description of the Drawings

Fig. 1 is a schematic sectional view of an embodiment (first embodiment) of a semiconductor device according to the present invention.

Fig. 2 is a diagram showing polar characteristics of ZnO.

Fig. 3 is a sectional view schematically showing the surface shape of a ZnO thin film formed on a zinc-polar surface of a ZnO substrate.

Fig. 4 is a diagram showing polar characteristics of a ZnO thin film formed on the zinc-polar surface of the ZnO substrate.

Fig. 5 is a schematic sectional view of a second

embodiment of the semiconductor device according to the present invention.

Fig. 6 is a schematic sectional view of a third embodiment of the semiconductor device according to the present invention.

Fig. 7 is a micrograph showing the surface shape of a ZnO thin film formed on a zinc-polar surface of a ZnO substrate.

Fig. 8 is a micrograph showing the surface shape of a ZnO thin film formed on an oxygen-polar surface of the ZnO substrate.

Fig. 9 is a diagram showing a crystal structure of ZnO.

Best Mode for Carrying Out the Invention

The embodiments of the present invention will be described below in detail with reference to the drawings.

Fig. 1 is a schematic sectional view of a Light Emitting Diode (hereafter referred to as "LED") as an embodiment (first embodiment) of a semiconductor device according to the present invention.

In Fig. 1, reference numeral 1 denotes a single crystal substrate primarily containing electrically conductive ZnO having an n-type conduction form (hereafter referred to as "ZnO substrate"), and the ZnO substrate 1 has a zinc-polar surface 1a and an oxygen-polar surface 1b.

In the LED, a light-emitting layer 2 is disposed on the zinc-polar surface 1a of the ZnO substrate 1, and a transparent electrode 3 of about 150 nm in film thickness made of Indium Tin Oxide (hereafter referred to as "ITO") is disposed on the surface of the light-emitting layer 2. Furthermore, a p-side electrode 4 having a total film thickness of about 300 nm is disposed on a substantially central portion of the surface of the transparent electrode 3, while a Ni film, an Al film, and a Au film are laminated sequentially in the p-side electrode 4.

An n-side electrode 5 having a total film thickness of about 300 nm is disposed on the oxygen-polar surface 1b of the ZnO substrate 1, while a Ti film and a Au film are laminated sequentially in the n-side electrode 5.

Specifically, the above-described light-emitting layer 2 is composed of a multilayer film in which an n-type contact layer 6, an n-type clad layer 7, an active layer 8, a p-type clad layer 9, and a p-type contact layer 10 are laminated sequentially. That is, the active layer 8 is held between the n-type clad layer 7 and the p-type clad layer 9, the n-type clad layer 7 is connected to the n-side electrode 5 with the n-type contact layer 6 and the ZnO substrate 1 therebetween, and the p-type clad layer 9 is connected to the transparent electrode 3 with the p-type contact layer 10 therebetween.

The active layer 8 is formed from CdxZn1-xO (where x satisfies $0 \leq x < 1$, and is 0.1, for example) which is a mixed crystal of CdO and ZnO and which has a film thickness of about 200 nm.

The active layer 8 emits light by recombination of an electron which is an n-type carrier and a hole which is a p-type carrier, and the wavelength of the emitted light is determined by the band gap energy.

Since carriers must be effectively confined in the active layer 8, the n-type clad layer 7 and the p-type clad layer 9 have the band gap energy larger than that of the above-described active layer 8, and are composed of MgyZn1-yO (where y satisfies $0 \leq y < 1$, and is 0.2, for example) which is a mixed crystal of MgO and ZnO. The n-type clad layer 7 is formed to have the film thickness of about 2,000 nm, and the p-type clad layer 9 is formed to have the film thickness of about 600 nm.

Both the n-type contact layer 6 and the p-type contact layer 10 are formed from ZnO of about 200 nm in film thickness.

A method for manufacturing the above-described LED will be described below.

Initially, a ZnO single crystal is prepared by a SCVT (Seeded Chemical Vapor Transport) method or the like. A surface perpendicular to the c axis direction of the crystal

axis is cut from the ZnO single crystal and is subjected to mirror polishing, so that a ZnO substrate is prepared and the polarity thereof is checked.

Examples of known methods for determining the polarity of a compound semiconductor, e.g., ZnO, having a piezoelectric property include a Coaxial Impact Collision Ion Scattering Spectroscopy (CAICISS) method (APPLIED PHYSICS LETTERS Vol. 72 (1998) p824), a Convergent Beam Electron Diffraction (CBED) method (APPLIED PHYSICS LETTERS Vol. 69 (1996) p337), and a Scanning Nonlinear Dielectric Microscopy (SNDM) method (Sentangijutsu Symposium "Atsudenzairyoto Danseiha Device" (High Technology Symposium "Piezoelectric Material and Elastic Wave Device"), (February, 2000) pp. 23-30). In the present embodiment, the polarity of the ZnO substrate is checked by the SNDM (Scanning Nonlinear Dielectric Microscopy) method.

That is, in the SNDM, when a potential is applied while a prove is made to scan the ZnO substrate 1, an intensity signal incorporating the polarity of the ZnO substrate 1 is detected.

On the other hand, when the applied potential is "0", since the potential is not applied, no intensity signal incorporating the polarity is detected.

In the SNDM method, when a potential is applied to the ZnO substrate 1, the intensity signal is displaced to the +

side or the - side compared with that in the case where the applied potential is "0".

Therefore, in the SNDM method, the intensity at an applied potential of "0" is taken as the reference signal, and the intensity signal when a potential is applied while the prove is made to scan the ZnO substrate 1 is taken as the polarity signal. Then, the polarity of the ZnO substrate can be determined based on the displacement of the polarity signal toward the + side or the - side relative to the reference signal.

In the present embodiment, the displacement of the polarity signal toward the - side relative to the reference signal indicates the + polarity (zinc-polarity), and the displacement of the polarity signal toward the + side relative to the reference signal indicates the - polarity (oxygen-polarity) based on the configuration of the SNDM.

Figs. 2(a) and 2(b) are diagrams showing the polar characteristics of the ZnO substrate 1. The horizontal axis indicates the scanning length (μm), and the vertical axis indicates the intensity (a.u.; arbitrary unit).

In Fig. 2, the direction indicated by an arrow X represents the polarity signal of the ZnO substrate 1, and the direction indicated by an arrow X' represents the reference signal when no potential is applied.

Therefore, it can be determined that when the polarity

signal is displaced toward the - side relative to the reference signal as shown in Fig. 2(a), the polar surface of the ZnO substrate 1 is a zinc-polar surface, and when the polarity signal is displaced toward the + side relative to the reference signal as shown in Fig. 2(b), the polar surface of the ZnO substrate 1 is an oxygen-polar surface.

After the polarity of the ZnO substrate 1 is determined as described above, a ZnO thin film is laminated on the zinc-polar surface 1a of the ZnO substrate 1 by the use of an Electron Cyclotron Resonance (hereafter referred to as "ECR") sputtering apparatus.

That is, the ECR sputtering apparatus separated into a plasma generation chamber and a film formation chamber is prepared, the ZnO substrate 1 is set at a predetermined position in the film formation chamber with the zinc-polar surface 1a up, and the ZnO substrate 1 is heated to a temperature of 300°C to 800°C.

Subsequently, a reactive gas, e.g., oxygen, and a plasma generation gas, e.g., argon, are supplied to the plasma generation chamber, and a microwave is discharged at a frequency (2.45 GHz) at which resonance occurs in the cyclotron, so that plasma is generated in the plasma generation chamber.

Thereafter, a high-frequency power (for example, 150 W) is applied to a sputtering target, and a sputtering target

substance (ZnO) is sputtered by the use of plasma generated in the plasma generation chamber, so that the n-type contact layer 6 made of ZnO is formed on the surface of the ZnO substrate 1 by reactive sputtering.

Next, the reactive sputtering is performed by the use of a target produced by sintering MgO and ZnO at a desired mixing ratio, so that the n-type clad layer 7 made of MgyZn1-yO (where $0 \leq y < 1$) is formed.

Likewise, the reactive sputtering is performed, and the active layer 8 made of CdxZn1-xO (where $0 \leq x < 1$), the p-type clad layer 9 made of MgyZn1-yO (where $0 \leq y < 1$), and the p-type contact layer 10 made of ZnO are formed sequentially.

The film thickness of each thin film is set at a desired film thickness by controlling the reaction time.

The Ti film and the Au film are formed sequentially on the surface of the oxygen-polar surface 1b of the ZnO substrate 1 so as to form the n-side electrode 5 by an evaporation method, the ITO film is formed on the surface of the p-type contact layer 10 by the evaporation method so as to form the transparent electrode 3 and, thereafter, Ni, Al, and Au are laminated sequentially so as to form the p-side electrode 4.

As described above, in the first embodiment, the light-emitting layer 2 composed of a ZnO-based multilayer film is

formed on the zinc-polar surface 1a of the ZnO substrate 1 and, thereby, ZnO-based thin films having excellent surface smoothness are laminated sequentially. As a result, the surface of the n-type clad layer 7 becomes a thin film including a smooth terrace 11 and a linear step 12, as shown in Fig. 3 (magnified diagram of a portion A shown in Fig. 1), and having excellent surface smoothness. Therefore, any crystal grain and any uneven portion do not remain on the surface, and the ZnO thin film having excellent surface smoothness can be attained.

The thin film having excellent surface smoothness, as shown in Fig. 3, can be attained with respect to not only the n-type clad layer 7, but also the n-type contact layer 6, the active layer 8, the p-type clad layer 9, and the p-type contact layer 10 in a similar manner.

Since the above-described ZnO-based thin films have excellent surface smoothness as described above, no current passes through grain boundaries, nor occur concentration of electric field on the surface of the ZnO film. Consequently, no scattering occurs during movement of electrons, and an LED having high mobility of electron, excellent crystallinity, and excellent electric characteristics can be attained.

In the above-described first embodiment, since the ECR sputtering apparatus is used and the ZnO-based thin films

are formed by the sputtering treatment, no expensive apparatus is required to be disposed separately, and the thin film formation can be performed inexpensively.

Furthermore, since the plasma generation chamber and the film formation chamber are separated, plasma damage to the ZnO thin film can be minimized, and a thin film having good quality can be attained.

In the present embodiment, the polarity of the ZnO thin film formed on the surface of the ZnO substrate 1 was further examined by the use of the SNDM.

That is, the sensitivity of the SNDM in the depth direction is determined based on the prove end radius of the prove and the dielectric constant of the sample, ZnO. In the case of ZnO, the detectable range in the depth direction is substantially equal to the prove end radius of the prove. Therefore, by making the above-described prove end radius smaller than the film thickness, the polarity of the ZnO thin film can be determined regardless of the polarity of the ZnO substrate 1 serving as the base.

Fig. 4 is a diagram showing the polar characteristics of the ZnO thin film. As in Figs. 2(a) and 2(b), the horizontal axis indicates the scanning length (μm), the vertical axis indicates the intensity (a.u.), the direction indicated by an arrow X represents the polarity signal of the ZnO substrate 1, and the direction indicated by an arrow

X' represents the reference signal when no potential is applied.

As is clear from Fig. 4, since the polarity signal is displaced toward the - side relative to the reference signal, the ZnO thin film has the zinc-polarity.

That is, the ZnO-based thin film formed on the zinc-polar surface of the ZnO substrate 1 has the zinc-polarity.

In the present embodiment, a double heterostructure is used for the light-emitting layer 2, in which the active layer 8 is held between the p-type clad layer 9 and the n-type clad layer 7. However, a pn junction structure, an MIS (Metal-Insulating layer-Semiconductor layer) structure, or a single heterostructure may be used.

Fig. 5 is a schematic sectional view of a Laser Diode (hereafter referred to as "LD") as a second embodiment of the semiconductor device according to the present invention.

In the LD, a light-emitting layer 14 is disposed on a zinc-polar surface 13a of a ZnO substrate 13 having electrical conductivity, and a p-side electrode 15 having a total film thickness of about 300 nm is disposed on the surface of the light-emitting layer 14, while a Ni film, an Al film, and a Au film are laminated sequentially in the p-side electrode 15.

An n-side electrode 16 having a total film thickness of about 300 nm is disposed on an oxygen-polar surface 13b of

the ZnO substrate 13, while a Ti film and a Au film are laminated sequentially in the n-side electrode 16.

Specifically, the above-described light-emitting layer 14 is composed of a multilayer film in which an n-type contact layer 17, an n-type clad layer 18, an n-type light guide layer 19, an active layer 20, a p-type light guide layer 21, a p-type clad layer 22, a current limiting layer 23, and a p-type contact layer 24 are laminated sequentially.

That is, the active layer 20 is held between the n-type clad layer 18 and the p-type clad layer 22 with the n-type guide layer 19 and the p-type guide layer 21 therebetween, respectively.

The n-type clad layer 18 is connected to the n-side electrode 16 with the n-type contact layer 17 and the ZnO substrate 13 therebetween, and the p-type clad layer 22 is connected to the p-side electrode 15 with the current limiting layer 23 and the p-type contact layer 24 therebetween.

Specifically, the active layer 20 has a multi-quantum well structure in which 2 to 5 layers of barrier layer composed of MgyZn1-yO (where y satisfies $0 \leq y < 1$, and is 0.1, for example) and well layer composed of CdxZn1-xO (where x satisfies $0 \leq x < 1$, and is 0.1, for example), each 3 nm, are alternately laminated.

When the refractive index of the active layer 20 is

larger than those of the n-type clad layer 18 and the p-type clad layer 22, the light can be confined in the active layer 20. However, when the light cannot be adequately confined since the active layer 20 is a thin film, the leakage of the light from the active layer 20 must be prevented. Consequently, the n-type light guide layer 19 having a refractive index between those of the n-type clad layer 18 and the active layer 20 is interposed between the active layer 20 and the clad layer 18, and the p-type light guide layer 21 having a refractive index between those of the p-type clad layer 22 and the active layer 20 is interposed between the active layer 20 and the clad layer 22 to constitute a part of an optical waveguide.

The n-type contact layer 17 of about 1,500 nm in film thickness made of ZnO is disposed on the zinc-polar surface 13a of the ZnO substrate 13. The n-type clad layer 18 of about 2,000 nm in film thickness made of MgyZn1-yO (where y satisfies $0 \leq y < 1$, and is 0.2, for example) is disposed on the surface of the n-type contact layer 17. Furthermore, the n-type light guide layer 19 of about 40 nm in film thickness made of ZnO is disposed on the surface of the n-type clad layer 18.

The active layer 20 having the above-described multi-well type structure is laminated on the surface of the n-type light guide layer 19. The p-type light guide layer 21

of about 40 nm in film thickness made of MgyZn1-yO (where y satisfies $0 \leq y < 1$, and is 0.2, for example) is disposed on the surface of the active layer 20. Furthermore, the p-type clad layer 22 of about 2,000 nm in film thickness made of MgyZn1-yO (where y satisfies $0 \leq y < 1$, and is 0.2, for example) is disposed on the surface of the p-type light guide layer 21.

In addition, in order to pass a current through an oscillation region alone, the current limiting layer 23 of 400 nm in film thickness made of MgyZn1-yO (where y satisfies $0 \leq y < 1$, and is 0.2, for example) is disposed on the surface of the p-type clad layer 22 while being in a predetermined shape having a groove portion 23a. The p-type contact layer 24 is disposed on the surface of the p-type clad layer 22 to have a cross section in the shape of a letter T while covering the current limiting layer 23.

The above-described LD is also produced by a method and procedure substantially similar to that in the first embodiment.

That is, initially, a ZnO single crystal is prepared by the SCVT method or the like. A surface perpendicular to the c axis direction of the crystal axis is cut from the ZnO single crystal and is subjected to mirror polishing, so that a ZnO substrate is prepared and the polarity thereof is checked by the SNDM.

Thereafter, as in the first embodiment, the ECR sputtering apparatus is prepared, the ZnO substrate 13 is set at a predetermined position in a film formation chamber with the zinc-polar surface 13a up, and the ZnO substrate 1 is heated to a temperature of 300°C to 800°C.

Subsequently, the reactive gas, e.g., oxygen, and the plasma generation gas, e.g., argon, are supplied to the plasma generation chamber, and a microwave is discharged, so that plasma is generated in the plasma generation chamber. A sputtering target substance (ZnO) is sputtered, and the n-type contact layer 17 made of ZnO is formed on the surface of the ZnO substrate 13 by reactive sputtering.

Likewise, the reactive sputtering is performed while the target substance is appropriately changed to a desired substance, and the n-type contact layer 17, the n-type clad layer 18, the n-type light guide layer 19, the active layer 20, the n-type light guide layer 21, the p-type clad layer 22, and the current limiting layer 23 are formed sequentially.

After the current limiting layer 23 is formed, the resulting ZnO substrate 13 provided with the films is temporarily taken out of the sputtering apparatus. A photoresist is applied to the surface of the above-described current limiting layer 23, the resist film is patterned by a known photolithographic technology, and an etching treatment

is performed with an alkaline solution, e.g., NaOH, so that the current limiting layer 23 is formed into a predetermined shape.

The above-described ZnO substrate 13 is set again at the predetermined position in the ECR sputtering apparatus, and the reactive sputtering is performed, so that the film of p-type contact layer 24 made of ZnO is formed to have a cross section in the shape of a letter T.

Thereafter, as in the first embodiment, the Ti film and the Au film are formed sequentially on the surface of the oxygen-polar surface 13b of the ZnO substrate 13 so as to form the n-side electrode 16 by an evaporation method, and Ni, Al, and Au are laminated sequentially on the surface of the p-type contact layer 24 by the evaporation method so as to form the p-side electrode 15.

As described above, in the second embodiment as well, the light-emitting layer 14 composed of a ZnO-based multilayer thin film is formed on the zinc-polar surface 13a of the ZnO substrate 13 as in the first embodiment. Therefore, ZnO-based thin films having a smooth terrace and a linear step can be attained. In this manner, since excellent surface smoothness is exerted, no current passes through grain boundaries, nor occur concentration of electric field on the surface of the ZnO film. Consequently, no scattering occurs during movement of electrons, the

mobility of electron becomes high, and the crystallinity becomes excellent, so that an LD having excellent electric characteristics can be attained.

In the above-described second embodiment, as in the first embodiment, since the ECR sputtering apparatus is used and the ZnO-based thin films are formed by the sputtering treatment, no expensive apparatus is required to be disposed separately, and the thin film formation can be performed inexpensively. Furthermore, since the plasma generation chamber and the film formation chamber are separated, plasma damage to the ZnO thin film can be minimized, and a thin film having good quality can be attained.

Fig. 6 is a schematic sectional view of a Thin Film Transistor (hereafter referred to as "TFT") as a third embodiment of the semiconductor device according to the present invention. The TFT is composed of an insulating ZnO substrate 25, a gate electrode 26 of 50 nm in film thickness disposed on a substantially central portion of the ZnO substrate 25, a gate insulating layer 27 of 200 nm in film thickness disposed on the ZnO substrate 25 while covering the gate electrode 26, an active layer 28 of 50 nm in film thickness disposed on the gate insulating layer 27, a channel protective layer 29 of about 200 nm in film thickness disposed on a substantially central portion of the active layer 28, and a source electrode 30 and a drain

electrode 31 which are disposed to cover a part of the channel protective layer 29 and which have film thicknesses of about 200 nm.

In the above-described TFT, a switching portion is composed of constituents other than the ZnO substrate 25, that is, the gate electrode 26, the gate insulating layer 27, the active layer 28, the channel protective layer 29, the source electrode 30, and the drain electrode 31. The switching portion made of them is disposed on a zinc-polar surface 25a of the ZnO substrate 25.

The gate electrode 26, the source electrode 30, and the drain electrode 31 are made to have low resistance since ZnO is doped with Ga, and the gate insulating layer 27 and the channel protective layer 29 are made to have high resistance since ZnO is doped with Ni.

The active layer 28 is formed from a non-doped ZnO thin film. The oxygen concentration in the thin film is adjusted by controlling the oxygen partial pressure during the formation of thin film and, thereby, the active layer 28 is formed to have n-type conduction.

The above-described TFT can also be readily produced by the use of the ECR sputtering and the photolithographic technology substantially similar to that in the first and the second embodiments.

That is, the ZnO substrate is prepared and, thereafter,

the polarity is determined. Subsequently, the ECR sputtering apparatus is used, and the reactive sputtering is performed while Ga-doped ZnO is served as a target substance, so that a ZnO film (ZnO:Ga) is formed on a zinc-polar surface 25a of the ZnO substrate 25.

The resulting ZnO substrate 25 is taken out of the ECR sputtering apparatus. A photoresist is applied to the above-described ZnO film, the resist film is patterned by a known photolithographic technology and, thereafter, an etching treatment is performed with an alkaline solution, e.g., NaOH, so that the gate electrode 26 is formed.

The reactive sputtering is performed while Ni-doped ZnO is served as a target substance, the gate insulating layer 27 is formed on the ZnO substrate 25 so as to cover the gate electrode. Subsequently, the reactive sputtering is performed while non-doped ZnO is served as a target substance and the oxygen partial pressure is controlled, so that the active layer 28 is formed.

Then, the reactive sputtering is performed while Ni-doped ZnO is served as a target substance, so that a ZnO film (ZnO:
Ni film) is formed. A photoresist is applied to the resulting ZnO film as in the above description, the resist film is patterned by the photolithographic technology and, thereafter, the etching treatment is performed with an

alkaline solution, e.g., NaOH, so that the channel protective layer 29 is formed.

Subsequently, the reactive sputtering is performed while Ga-doped ZnO is served as a target substance, a photoresist is applied to the resulting ZnO:Ga film as in the above description, the resist film is patterned by the photolithographic technology and, thereafter, the etching treatment is performed with an alkaline solution, e.g., NaOH, so that the source electrode 30 and the drain electrode 31 are formed.

As described above, in the third embodiment, since the TFT is formed from a ZnO-based multilayer film, even when the active layer 28 is exposed to light, a change in the electrical conductivity can be suppressed.

That is, in the case where an active layer is formed from amorphous silicon (a-Si) in a previous manner, since a-Si becomes electrically conductive by the application of light, the characteristics of the switching element may be deteriorated. On the other hand, in the third embodiment, since the active layer 28 is formed from a ZnO thin film having a band gap of about 3.3 eV and having transparency to the visible light, even when the light is applied to the active layer 28, a change in the electrical conductivity can be suppressed, and deterioration of the characteristics of the switching element can be prevented.

Furthermore, by integrally forming the TFT as an upper portion of a photoelectric conversion element or the LED shown in the first embodiment, the amount of light incident to the photoelectric conversion element can be increased or the amount of light emitted from the light-emitting layer can be increased and, therefore, the proportion of opening can be increased.

The present invention is not limited to the above-described embodiments.

In the above-described embodiment, the ZnO-based thin films are formed by the ECR sputtering method. However, an inductively coupled plasma (ICP) sputtering method, a helicon wave excited plasma (HWP) sputtering method, an ion beam sputtering method, a cluster beam sputtering method, or the like may be used. Alternatively, the ZnO-based thin films may be formed by the use of a molecular-beam epitaxy (MBE) method, a metal organic chemical vapor deposition (MOCVD) method, a laser molecular-beam epitaxy (laser MBE) method, a laser abrasion method, or the like other than the sputtering method.

Specific examples of the present invention will be described below.

The inventors of the present invention used the ECR sputtering apparatus, formed a ZnO thin film on a zinc-polar surface of a ZnO substrate, and prepared a test piece for

Example. Furthermore, a ZnO thin film was formed on an oxygen-polar surface of a ZnO substrate, and a test piece for Comparative example was prepared.

That is, an ECR sputtering apparatus separated into a plasma generation chamber and a film formation chamber was prepared. A ZnO substrate was set at a predetermined position in the film formation chamber, and the substrate was heated to a temperature of 620°C.

Subsequently, each of 20 sccm of argon gas serving as a sputtering gas and 10 sccm of O_2 gas serving as a reaction gas was supplied to the plasma generation chamber, and micro-discharge was performed, so that plasma was generated. A high-frequency electric field of 150 W was applied to a sputtering target, and a sputtering treatment was performed, so that a ZnO thin film was formed on a zinc-polar surface of a ZnO substrate, another ZnO thin film was formed on an oxygen-polar surface of another ZnO substrate and, thereby, test pieces for Example and Comparative example were prepared.

The inventors of the present invention observed the surface shapes of the ZnO thin films with an atomic force microscope.

Fig. 7 shows the ZnO thin film of Example. Fig. 8 shows the ZnO thin film of Comparative example, formed on the oxygen-polar surface of the ZnO substrate.

As is clear from this Fig. 8, the ZnO thin film of Comparative example is in the shape of islands and, therefore, grain boundaries are present.

On the other hand, as shown in Fig. 7, it was ascertained from the ZnO thin film of Example that a thin film having the surface shape including a smooth terrace and a substantially linear step was able to be attained.

Therefore, it was made clear that the ZnO thin film formed on the zinc-polar surface of the ZnO substrate had significantly excellent surface smoothness compared with that of the ZnO thin film formed on the oxygen-polar surface of the ZnO substrate.

The inventors of the present invention calculated the root-mean-square surface roughness RMS of the ZnO thin film, and evaluated the surface roughness.

As a result, the root-mean-square surface roughness RMS of the ZnO thin film of Comparative example was 20.4 nm, whereas the root-mean-square surface roughness RMS of the ZnO thin film of Example was 1.4 nm. Consequently, it was made clear that the surface smoothness of the ZnO substrate was significantly improved by forming the ZnO thin film on the zinc-polar surface compared with that in the case where the ZnO thin film was formed on the oxygen-polar surface.

The inventors of the present invention conducted a hole measurement, and calculated the electron mobility.

When the crystallinity is excellent, the mobility is increased because electrons are not scattered due to crystal defects during movement. However, if crystal defects are present, the mobility is decreased because electrons are scattered due to crystal defects during movement.

Therefore, the level of crystallinity and the electric characteristics can be evaluated by calculating the electron mobility.

The inventors of the present invention laminated sequentially a Ti film and a Au film on each of the ZnO thin films of Example and Comparative example by an evaporation method to form an electrode, and conducted the hole measurement so as to measure the electron mobility.

As a result, the electron mobility was 2 cm2/V·sec in Comparative example, whereas the electron mobility was a large 30 cm2/V·sec in Example. Consequently, it was ascertained that both the crystallinity and the electric characteristics of Example were excellent compared with those of Comparative example.

Industrial Applicability

As described above, the electronic components according to the present invention are used as components for image equipment, and are particularly suitable for use as light-emitting elements of optical pickups used in image equipment.